AL

Case: Isaacs 3-6
Filing Date: March 10, 2004

(12) INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(19) World Intellectual Property Organization
International Bureau

(43) International Publication Date
30 May 2003 (30.05.2003)

PCT

(10) International Publication Number
WO 03/044897 A1

(51) International Patent Classification[7]: H01Q 15/10, G02B 1/10, 5/20, 1/00

(21) International Application Number: PCT/GB02/03608

(22) International Filing Date: 5 August 2002 (05.08.2002)

(25) Filing Language: English

(26) Publication Language: English

(30) Priority Data:

0127514.8	16 November 2001 (16.11.2001)	GB
0211464.3	20 May 2002 (20.05.2002)	GB

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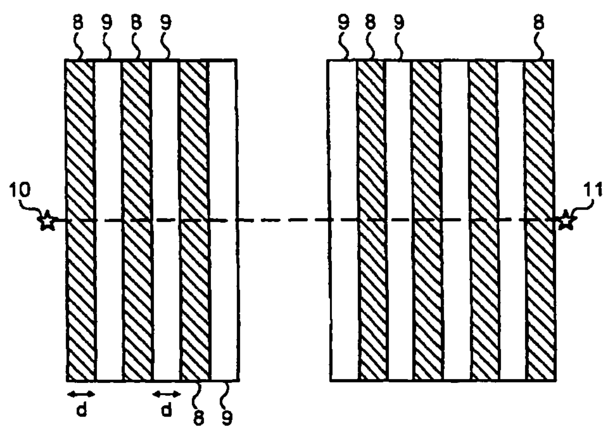
(81) Designated States *(national)*: AE, AG, AL, AM, AT, AU, AZ, BA, BB, BG, BR, BY, BZ, CA, CH, CN, CO, CR, CU, CZ, DE, DK, DM, DZ, EC, EE, ES, FI, GB, GD, GE, GH, GM, HR, HU, ID, IL, IN, IS, JP, KE, KG, KP, KR, KZ, LC, LK, LR, LS, LT, LU, LV, MA, MD, MG, MK, MN, MW, MX, MZ, NO, NZ, OM, PH, PL, PT, RO, RU, SD, SE, SG, SI, SK, SL, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VN, YU, ZA, ZM, ZW.

(84) Designated States *(regional)*: ARIPO patent (GH, GM, KE, LS, MW, MZ, SD, SL, SZ, TZ, UG, ZM, ZW), Eurasian patent (AM, AZ, BY, KG, KZ, MD, RU, TJ, TM), European patent (AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE, SK,

[Continued on next page]

(54) Title: MULTILAYER IMAGING DEVICE WITH NEGATIVER PERMITTIVITY OR NEGATIVE PERMEABILITY LAYERS



(57) Abstract: An imaging device arranged to image near field as well as far field components form an object comprises a stack of layers (8) spaced apart from each other, the layers having a negative real part of electrical permittivity or magnetic permeability in a direction normal to the layers, and being constructed from microstructured material comprising an array of elements spaced apart from each other by a distance less than the wavelength of radiation to be imaged. The layers may be spaced by medium of positive real part of electrical permittivity or magnetic permeability, both the layer and the spacing being isotropic. In an alternative embodiment, the layers are in pairs in which the component of electrical permittivity or magnetic permeability in a direction normal to the layers is alternately negative and positive, while the electrical permittivity or magnetic permeability in a transverse direction is positive or negative, respectively. In an alternative embodiment, the magnitude of the component of the electrical permittivity or magnetic permeability is very large in a direction normal to the incident face.

WO 03/044897 A1

TR), OAPI patent (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, ML, MR, NE, SN, TD, TG).

Published:
— *with international search report*

MULTILAYER IMAGING DEVICE WITH NEGATIVE PERMITTIVITY OR NEGATIVE PERMEABILITY LAYERS

This invention relates to imaging devices.

The invention is especially concerned with imaging devices which are capable of imaging subwavelength features.

The focussing of a conventional lens in the far field can be explained in the following way. Referring to Figure 1, which shows in symbolic form the focussing of an object 1 by a conventional lens 2, the two dimensional object is visible because it emits an electromagnetic field. It is convenient to decompose this field into the Fourier components defined by k_x, k_y and polarisation defined by σ,

$$\mathbf{E}_{object}(x, y) = \sum_{\sigma, k_x, k_y} \mathbf{E}_\sigma(k_x, k_y)\exp(ik_x x + ik_y y) \tag{1}$$

Maxwell's equations tell us how the electromagnetic field propagates away from the object plane along the z-axis,

$$\mathbf{E}(x, y, z) = \sum_{\sigma, k_x, k_y} \mathbf{E}_\sigma(k_x, k_y)\exp(ik_x x + ik_y y + ik_z z) \tag{2}$$

where,

$$k_z = \sqrt{\omega^2 c_0^{-2} - k_x^2 - k_y^2} \tag{3}$$

Obviously when we move out of the object plane 1 the amplitude of each Fourier component changes (note the z-dependence) and the image 3 becomes blurred. Provided that k_z is real,

$$\omega^2 c_0^{-2} > k_x^2 + k_y^2 \tag{4}$$

it is only the phase that changes with z and a conventional lens is designed to correct for this phase change. Thus if we want to focus an image a distance d from the object we must introduce a lens with a k-dependent transmission coefficient,

$$T_L(k_x, k_y) = \exp\left(-i\sqrt{\omega^2 c_0^{-2} - k_x^2 - k_y^2}\, d + i\alpha\right) \tag{5}$$

This corrects for the phase change that would otherwise take place. Note that the image is still in focus even when $\alpha \neq 0$ because a constant phase shift will not blur the image.

A conventional lens has limited resolution. Because it can only act on the *phase*, it is limited to correcting the amplitude of those Fourier components for which (4) is satisfied. Thus the largest wavevector is,

$$k_{\max} = \omega c_0^{-1} \tag{6}$$

From the theory of Fourier transformations, limiting the maximum wavevector limits the amount of spatial detail that can be resolved to,

$$\Delta \approx \frac{2\pi}{k_{\max}} = \frac{2\pi c_0}{\omega} = \lambda_0 \tag{7}$$

where λ_0 is the wavelength of light. No conventional lens can do better than this.

Although the resolution of the image is limited by (7), the object may contain arbitrarily fine detail. The very finest detail will involved large k-vectors which violate (4) and therefore cannot be focussed, as discussed above. The nature of evolution along the z-axis changes for large wavevector because we must write,

$$k_z = i\sqrt{k_x^2 + k_y^2 - \omega^2 c_0^{-2}} \tag{8}$$

Substituting an imaginary value of k_z into (2) shows that these Fourier components instead of changing their phase as they propagate along the z-axis, instead change their amplitude: they decay away exponentially. These components are termed 'evanescent wave', or 'the near field': more than a few wavelengths away from the object, their contribution to the overall field is negligible. For this reason it has been generally accepted that the 'near field' will not contribute to an image. The only way it could do so would be it the lens acted as an amplifier for the near field components. Remarkably there is such a device and even more remarkably the prescription is very simple: a slab of material with,

$$\varepsilon = -1, \quad \mu = -1 \tag{9}$$

not only will focus the far field by correcting the phase, but also will correct the amplitude of the near field and bring that to a focus too. This is the lens called 'the perfect lens' (Negative Refraction makes a Perfect Lens - Phys. Rev. Lett. 85, 3966, (2000)) because it will focus all components of the field and therefore can form a perfect image. It will be recognised that Equation (9) implies a refractive index n = -1.

In the 'extreme near field',

$$\omega^2 c_0^{-2} \ll k_x^2 + k_y^2 \qquad (10)$$

Thus all length scales are now much smaller than the wavelength of light. Electric and magnetic fields become entirely separate and the electric field becomes electrostatic in nature (the electrostatic limit). Figure 2 is a schematic plot of the electric potential in the vicinity of a slab 4 of material, thickness d, $\varepsilon = -1$. In the plane $z=2d$, the electric field is restored to its value in the plane $z=0$.

It follows that imaging of both far field and near field information from an object can be achieved by a material having only a permittivity ε = -1, rather than a refractive index of n = -1, in the electrostatic limit where the object is very close to the lens. Similarly, for magnetic fields, imaging of both far field and near field information from an object can be achieved by a material having only a permeability μ = -1, in the magnetostatic limit where the object is very close to the lens.

If the medium shown in Figure 2 is less than perfect i.e. slightly resistive, so that

$$\varepsilon = -1 + i\tau \tag{11}$$

it turns out that resolution is lost. However, if as proposed in Electronics Letters 27 September 2001, Vol 37, No 20, the slab 4 is cut into several slices 5-7, the impairment of resolution is reduced. This is because the wavefield has smaller fluctuations in amplitude as shown in Figure 3, which is a schematic plot of the electric potential in the vicinity of spaced slices of medium, and because maximum dissipation occurs where there is maximum amplitude. Reducing the maximum amplitude reduces the effect of dissipation, and therefore increases the resolution.

However, there are severe practical problems with this approach. For the material mentioned in the Phys. Rev. Lett. paper viz silver, the wavelength of operation is 356nm, in the near ultraviolet. This enforces very short length scales. In the same paper, the silver film was 80nm thick, and the source-lens and lens-imaging spacing were 40nm. There is a significant loss in silver of this wavelength, so that thicker films (with correspondingly larger source-lens spacing) could not be used. The spaced slabs of the Electronics Letter paper would partially alleviate this problem (silver is again mentioned), but nevertheless the loss would still be high and the length scales unusably short.

The Applicants have approached the problem of resolution in an imaging device by consideration of the dispersion relation

$$\omega^2 c_0^{-2} = k_0^2 = \varepsilon_z^{-1}\left(k_x^2 + k_y^2\right) + \varepsilon_x^{-1} k_z^2 \tag{12}$$

This describes the propagation of the Fourier components of the electric field of an image through a medium which for simplicity is assumed to be isotropic in the x-y plane, so that only ε_x and ε_z are distinct. In the equation, ω is the angular frequency of the radiation, c_0 is the speed of light *in vacuo*, k_0 is the vacuum wavevector of the radiation ($k = 2\pi/\lambda$), k_x, k_y, k_z are the components of the wavevector in the x, y, z directions respectively, ε_x and ε_z are the permittivity in the x and z directions respectively. Conventionally, we take z to be the direction of propagation, and the x, y plane to be transverse directions.

The Applicants have realised that a regime which decouples k_x and k_z, and so makes k_z independent of k_x, will have the result that the image propagates independently of the value of k_x, the image content. No defocusing of the electromagnetic waves takes place as they are transmitted through such a medium. In such a medium, therefore, the radiation propagates without change of phase of any of the transverse Fourier component. Thus the field pattern that emerges from the medium is identical to that which entered it, and the device transfers or focuses the image perfectly. In order to observe a focussed image it is not even essential that each Fourier component has *zero* phase change, merely that all components have *the same* phase change.

The Applicants have appreciated that this requires an effective medium having an almost zero dielectric response along the x-axis, and almost infinite along the z-axis. In the equation (12) above, if $\varepsilon_z = \infty$, changes in k_x or k_y will not affect k_z.

An analogous situation applies with regard to permeabilities.

One way of achieving this result is if one works in, say, the electrostatic limit, and alternates thin layers of equal thickness, with

$\varepsilon_x = \varepsilon_y = \varepsilon_z = -1$, for one set of layers, and

$\varepsilon_x = \varepsilon_y = \varepsilon_z = 1$ for the other set.

The effective permittivity of such a medium is given by

$$\varepsilon_x\,(\text{effective}) = \varepsilon_y\,(\text{effective}) = 0$$

$$\varepsilon_z\,(\text{effective}) = \infty$$

According to a first form of the invention, an imaging device comprises a stack of layers spaced apart from each other, each layer having a negative real part of electrical permittivity or magnetic permeability, and each layer comprising an array of elements spaced apart from each other by a distance less than the wavelength of radiation to be imaged by the device.

Advantageously, the thickness of each layer lies within the range of 1/5 of the wavelength of the incident radiation and 1/50 of the wavelength of the incident radiation. Preferably, the number of layers lies within the range of from 2 to 10. The layers may be spaced by spacers having a positive real part of electrical permittivity or magnetic permeability, each spacer lying within the range of from 1/5 of the wavelength of the incident radiation and 1/50 of the wavelength of the incident radiation. More than 10 layers may be provided if desired.

Another way of achieving the same result of

$$\varepsilon_x\ (\text{effective}) = \varepsilon_y\ (\text{effective}) = 0$$

$$\varepsilon_z\ (\text{effective}) = \infty$$

follows when we alternate,

$$\varepsilon_x = \varepsilon_y = -1, \quad \varepsilon_z = +1 \ \text{ with,}$$

$$\varepsilon_x = \varepsilon_y = +1, \quad \varepsilon_z = -1$$

This also gives a propagating wave in the z-direction, but one whose phase does not change with distance.

According to a second form of the invention, an imaging device comprises at least two layers, the real part of the component of the electrical permittivity or magnetic permeability of one layer in a direction normal to the layers being negative, and positive in a transverse direction, and the real part of the component of the electrical permittivity or magnetic permeability of the other layer in the direction normal to the layers being positive, and negative in the transverse direction.

Advantageously, the thickness of each layer lies within the range of 1/5 of the wavelength of the incident radiation and 1/50 of the wavelength of the incident radiation. Preferably, the number of layers lies within the range of 2 to 10.

A third way to realise infinite permittivity/permeability in the direction parallel to the incident wave applies to the magnetic case.

According to a third form, the invention provides an imaging device in which the ratio of the magnitude of the component of the magnetic permeability or electrical permittivity of the material of the device in a direction normal to the incident face to the magnitude of the component of the magnetic permeability or electrical permittivity in a transverse direction, is at least 10.

Advantageously, the ratio is at least 30, preferably at least 100.

To produce the required value of the electrical permittivity/magnetic permeability in the three realisations of the invention, there may be used microstructured material comprising an array of elements spaced apart from each other by a distance less than the wavelength of radiation to be imaged by the device, preferably less than half of the wavelength, advantageously less than one fifth, although the spacing could be less (less than one tenth or less than one hundredth of that wavelength).

The microstructured material could include Swiss rolls, split rings, grids of wires or an array of dipoles, for example, as described in WO 00/41269, WO 00/41270, WO 01/67553, WO 01/67750, WO 01/67549, WO 01/67125, WO 01/67126 and WO 02/03500, the contents of which are incorporated herein by reference.

In the case of magnetic permeabilities, the magnitude of the component of magnetic permeability is a transverse direction, or two transverse directions at right angles to each other, may be unity (this may be the case of with Swiss rolls or split rings), in which case the requirements that the ratios are at least 10, 30 or 100 reduce to the requirement that the magnitude of the component of the magnetic permeability in a direction normal to the incident face is at least 10, 30 or 100 respectively.

Imaging devices constructed in accordance with the invention will now be described in greater detail, by way of example, with reference to the accompanying drawings, in which:

Figure 1 shows the focussing of a lens in symbolic form;

Figure 2 is a schematic plot of the electric potential in the vicinity of an imaging device in the form of a slab of material having permittivity $\varepsilon = -1$;

Figure 3 is a schematic plot of the electric potential in the vicinity of an imaging device in the form of slices of negative permittivity material;

Figure 4 is a schematic sectional view of a first form of imaging device in accordance with the invention;

Figure 5 is a representation of a first form of material for use as one of the alternate layers of the imaging device of Figure 4;

Figure 6 shows on an enlarged scale a fragment of one of the wires of the material of Figure 5;

Figure 7 is a representation of a second form of material for use as one of the alternate layers of the imaging device of Figure 4;

Figure 8 is a representation of a third form of material for use as one of the alternate layers of the imaging device of Figure 4;

Figure 9 is a schematic sectional view of a second form of imaging device in accordance with the invention;

Figure 10 is a representation of a first form of material suitable for use as one of the alternate layers of the imaging device of Figure 9;

Figure 11 is a representation of a first form of material suitable for use as the other alternate layer of the imaging device of Figure 9;

Figure 12 is a representation of a second form of material suitable for use as both alternate layers in the imaging device of Figure 9;

Figure 13 is a representation of a third form of material suitable for use as both alternate layers in the imaging device of Figure 9;

Figure 14 is a side view of a third form of imaging device in accordance with the invention;

Figure 15 is a front view of the third form of imaging device; and

Figure 16 is a plot of magnetic permeability against frequency of radiation to be imaged, for the imaging device of Figures 14 and 15.

Referring to Figure 4, the first form of imaging device according to the invention comprises a multi-layer stack of alternating negative 8 and positive 9 isotropic layers, that is, negative and positive in terms of the real part of its permittivity or permeability. The negative layers take the form of microstructured dielectric material (Figure 5 and 6) with negative real part of permittivity, or microstructured magnetic material (Figure 7 or Figure 8) with negative real part of permeability. The layers are each thickness d, as is the spacing between the layers, and both the object 10 and the image 11 are spaced from the front and rear faces, respectively, of the stack by a distance d/2. Central layers of the stack are not illustrated. For convenience, the stack has a negative layer at each end.

The microstructured material consists of an array of elements spaced by a distance less than the wavelength of radiation to be imaged by the imaging device, advantageously spaced by a distance less than one half of that wavelength, preferably spaced by a distance less than one fifth of that wavelength, but could be spaced by a lesser amount (less than one tenth, or less than one hundredth of that wavelength).

The material of the negative layers is isotropic.

The negative layers are spaced by air or with an inert low permittivity filler such as Rohacell (Trade Mark), also isotropic. The layers 9 have a positive real part of permittivity and permeability, and can thus be used to space dielectric or magnetic material.

Each individual microstructured layer acts as a perfect lens, and images the source 10 at a distance d/2 from its front surface to an intermediate image located d/2 from its rear surface. The intermediate image serves as the source for the succeeding layer. The final layer delivers the image to a final position d/2 beyond the exit face.

When the layers are thin, such a stack provides an imaging or transfer device in which the image (field pattern) very close to the front face is transferred to the rear face. Thus it is similar in behaviour (but not in operation) to the mineral Ulexite, known as TV Rock, or to a fibre-optic face-plate. However, the present device has an advantage over such known structures, because it has no lateral structure (as in the fibre-optic bundle) to limit resolution and impose unwanted artefacts on the image.

In the limit of very thin layers, the medium in the imaging device of Figure 4 is not spatially dispersive; that is the radiation is transmitted through the medium without spreading out (and subsequent concentration).

If we apply the arguments of form birefringence (see e.g. Born & Wolf, Principles of Optics, Section 14.5.2) to a stack of very thin layers with alternating positive and negative index, we find that the effective refractive index, n_{eff}, is zero, so there is no phase change of the radiation as it proceeds through the materials. In other words, it appears as if the material is absent, rather than in fact occupying space.

There are several advantages of the multi-layered stack of Figure 4 over a uniform slab of microstructured medium with the real part of permittivity $\varepsilon = -1$ or the real part of permeability $\mu = -1$. First, the source is closer to the front face of the device, and hence the decay of the field before the entrance face is reduced to a minimum. Second, less amplification of the evanescent field is needed, and that is distributed more evenly through the material. Since, therefore, each layer needs to contribute less amplification, the whole structure is more tolerant of loss in the medium. Third, the thinner layers are tolerant of a wider bandwidth of operation. Fourth this structure, if formed with non-flat surfaces, can image between such surfaces in a way no lens would be able to.

The thickness of the layers 8, 9 may lie within the preferred range of 1/5 to 1/50 of the wavelength of the incident radiation, and the number of pairs 8, 9 of layers may lie within the preferred range of 2 to 10. In the case of the very thin layers referred to, the thickness may be less than 1/50 of the wavelength of operation, with the number of layer pairs being greater to preserve a suitable thickness for the whole stack. More than 10 pairs of layers may be provided if desired.

Microstructured materials can be made to have negative real part of permittivity (e.g. Pendry et al J Phys. Conden. Mat **10**, 4785 (1998)) and/or permeability (Pendry et al IEEE Trans Microwave Theory & Tech. **47** 2075 (1999)) and, indeed, to have a negative refractive index (R A Shelby, D R Smith & S Schultz Science **292**, 77 (2001)). The permittivity and permeability of microstructured materials are complex, the imaginary part of relating to the loss encountered by a propagating wave through the material (Pendry, Physics World September 2001 pp47-51).

In a preferred embodiment, the multi-layer stack of microstructured material is designed to have ε or $\mu = -1$ at the operating wavelength, and is combined with layers of air or other inactive medium which has ε or $\mu = +1$ at the operating wavelength.

Variations are of course possible. The layers of the stack of Figure 4 do not have to be of equal thickness. For example, successive pairs of negative/positive bi-layers 8, 9 may be of equal thickness even though one of the bi-layers of each pair is thicker than the other. However, the layers 9 may be of variable thickness throughout the block, provided that the thicknesses are matched by respective positive layers 8 somewhere in the block, i.e. a thick negative layer at one position is balanced by a thick positive layer somewhere else in the block.

The operating wavelength of such blocks can lie in the R.F., including microwave and mm regions, of the electromagnetic spectrum.

Referring to Figures 5 and 6, the first form of microstructured material comprises a lattice of fine wires (Pendry et al J.Phys. Conden. Mat 10, 4785 (1998). A fragment of the lower end of one of the vertical wires is shown in Figure 6. The wires are thus solid. The lattice has wires 12-14 extending in three orthogonal directions. The wires can be made of a highly conductive metal such as copper or gold-plated tungsten. A preferred range of lattice spacing is 1mm to 50mm, and a typical lattice spacing is 5mm. A preferred range for the diameter of the wires is from 1μm to 50μm for operation in the range of from 0.7 GHz to 60 GHz A typical diameter of wire 20μm for operation in the region of 10 GHz. The lattice is arranged with its axes parallel to those of the slabs 8. Gold-plated tungsten wires are stiff, and would be self-supporting. Copper wires could be woven into a two dimensional mesh, threaded with wires in the third dimension. Or a two dimensional mesh could be etched tracks on a printed circuit board.

The lattice may form a material with the real part of the permittivity $\varepsilon = -1$. This can be achieved by suitable selection of the unit cell size i.e. the wire spacing, but detailed formulae are given in the J.Phys. Conden. Mat. paper referred to. The layers 8 are more than a unit cell thick (typically a few mm). The device can be constructed from such layers of material interleaved with air by means of a frame, or with an inert, low permittivity filler such as Rohacell. The real part of the permittivity of air is 1.00 and that of Rohacell 1.07.

Referring to Figure 7, the second form of microstructured material comprises a three-dimensional array of material having a negative real part of magnetic permeability. Figure 7 shows a unit cell of the material. The structure is repeated to build up the

layers 8, the unit cells being arranged with their axes parallel to the axes of the slabs. Each element 15-17 of the unit cell consists of a pair of split conducting rings, such as 15a, 15b, the splits being on opposite sides of the rings. The construction and fabrication of such split rings into a three-dimensional array is described in Pendry et al IEEE Trans. Microwave Theory and Tech **47** 2075 (1999).

The assembly of split ring resonator elements, as described by Pendry et al in the paper referred to can be constructed to have a permeability μ = -1 also in the microwave region by suitably varying the microstructure e.g. the ring diameter of the gap between the rings. The layer thickness must be at least one structural element, typically 5 mm. The layers 8 are interleaved with air held apart by a frame, or Rohacell to form layers 9.

Referring to Figure 8, the third form of microstructured material comprises an array of "Swiss rolls" arranged in a three-dimensional array. The "Swiss rolls" can consist of plastic-backed sheets of metal that have been wound into a roll in which the metal surfaces never touch each other. When a current flows in this structure, it charges the capacitance between the inner and outer winding. Such a structure has negative permeability over a certain range of frequencies. These structures are described in Pendry et al IEEE Trans. Microwave Theory and Tech **47** 2075 (1999), Pendry, Physics World, September 2001 pp 47-51, Wiltshire et al Science **291** 2001 pp 849-851. In the form of stacking shown in Figure 8, the "vertically" arranged rolls 18 are alternated with "horizontal" rolls 19, while another set of rolls 20 extends normal to the plane of the drawings. The axes of the rolls are parallel to the axes of the slabs 8. Dimensions are chosen to give a real part of magnetic permeability μ = -1. Typical thicknesses of

the layers 8 are 10mm – 50mm. A roll of 18μm thick conducting film on a 12μm thick Kapton® substrate, may be arranged with pitch spacing 16mm.

For example, 250mm long panels of this wound on an 8mm diameter mandrel form Swiss Rolls with about 9.7 turns and a diameter of ~8.5mm. These work at about 35 MHz. In Figure 8, the rolls 18, 20 could be as long as required; the rolls 19 could be ~42mm long (five times outside diameter). The pitch spacing or unit cell size could be ~17mm (twice outside diameter). Different material, operating at different frequencies, would obviously give widely different numbers. The structure in Figure 8 could be assembled with e.g. Rohacell packaging between the rolls to keep everything in place, and the layers themselves could be held in a frame or assembled with blocks of Rohacell or polystyrene foam.

Of course, other isotropic microstructured materials may be used to provide a real component of electrical permittivity $\varepsilon = -1$ or magnetic permeability $\mu = -1$. It is not essential for the real part of the electrical permittivity ε, or magnetic permeability μ to be equal to -1. Other negative values are possible. Suitable thicknesses for the layers 8, 9 can be calculated using the expression for form birefrigence given in Section 14.5.2 of Born and Wolf, Principles of Optics. Equally, the layers of electrical permittivity such as those of Figure 5 may be superimposed on the layers of magnetic permeability such as those of Figures 7 and 8. For example, the wires of Figure 5 could be arranged to extend along the axes of the columns of rings 15, 16, 17, or along the axes of the Swiss rolls. Alternatively, an imaging device with adjacent layers of $\varepsilon = -1$, $\mu = -1$ could be used. The resulting structure would give a refractive index $n = -1$.

Referring to Figure 9, the second form of imaging device comprises a multi-layer stack of alternating layers 21, 22 of opposite anistropy, viz, negative anisotropy and positive anisotropy. The layers are of equal thickness. The object and the image are at the beginning and end, as in Figure 4. For the layers 21 (negative anisotropy), the real part of the electrical permittivity ε or magnetic permeability μ in a direction normal to the layers (the z-direction) is given by $\varepsilon = -1$ or $\mu = -1$, and is given by $\varepsilon = 1$ or $\mu = 1$, respectively, in two transverse directions at right angles to each other (the x and y directions). For the layers 22 (positive anisotropy), the real part of the electrical permittivity ε or magnetic permeability μ in a direction normal to the layers (the z-direction) is given by $\varepsilon = 1$ or $\mu = 1$, and is given by $\varepsilon = -1$ or $\mu = -1$, respectively, in two transverse directions at right angles to each other (the x and y directions).

In the case of anisotropic material wherein the permittivity varies between the layers, the general requirement is that the layers 22 (positive anisotropy) should have a permittivity of dielectric form ε in the z-direction, and a permittivity of metallic or plasma form in a transverse direction, preferably two transverse direction at right angles (x, y directions). The metallic form of the permittivity is given as:

$$\varepsilon = 1 - \frac{\omega_p^2}{\omega(\omega + i\gamma)} \tag{13}$$

where ω_p is the plasma frequency of the metal, and γ is the damping or loss in the material. ω_p, in turn, depends on the number of charge carriers and their effective mass. For the layers 21 (negative anisotropy), the permittivities are reversed in the sense that it

is of metallic form as given by the above equation in the z-direction and of dielectric form ε in the x and y directions. The permittivities of $\varepsilon = 1$, $\varepsilon = -1$ referred to above are particular examples of this general requirement.

As analogous situation applies for permeabilities.

The imaging device works equally well whether the radiation is incident on its left face or its right face. While a stack of ten layers have been illustrated in Figure 9, in fact any even number of layers would be suitable, even just two layers of opposite anistropy.

In the electrostatic case, if it is assumed that the real parts of the permittivities are either 1 or -1, an electrostatic field injected at one end of just one pair of layers would have increasing phase in the first layer and decreasing phase in the second, so that there is no phase change at the end of the second layer compared to the beginning of the first, provided the layers are of equal thickness. The phase of an electromagnetic wave rotates in one sense in the first layer and is unwound by the same amount in the second layer. Because there is no net phase change across the two layers, the image is in focus.

The phase compensating effect of the second layer clearly depends on it being the same thickness as the first layer and the real part of the permittivities being ± 1. However, the layers could be of different thickness if the permittivities also differ between the two layers, in such a way that the second layer unwinds the phase change caused by the first layer. This is also true of a stack of layers. The requirement is that the product of thickness and permittivity must vanish over the whole block thickness. That is the same

as the condition for zero phase change. So any of these combinations would work: pairs of layers of the same thickness, but equal and opposite permittivity ε; pairs layers of different thickness and permittivity such that the total product of thickness and permittivity is zero; a medium with a variety of layers of different thickness and permittivities, such that the total product of thickness and permittivity is zero.

The thickness of the layers 21, 22 may lie in the preferred range of 1/5 to 1/50 of the wavelength of operation, and the number of pairs 21, 22 of layers may lie in the preferred range of 2 to 10.

The layers 21, 22 may be formed from microstructured material consisting of an array of elements spaced by a distance less than the wavelength of radiation to be imaged by the imaging device, advantageously spaced by a distance less than one half of that wavelength, preferably spaced by a distance less than one fifth of that wavelength, but could be spaced by a lesser amount (less than one tenth, or less than one hundredth of that wavelength).

In the case of microstructured dielectric material, Figure 10 illustrates four layers of wire grids 23 designed to give (positive anisotropy) the real part of the permittivities in the x, y and z directions as follows:

$$\varepsilon_x, \varepsilon_y = -1, \quad \varepsilon_z = 1$$

Figure 11 illustrates a set of wire "bristles" 24 designed to produce (negative anisotropy)

$$\varepsilon_x, \varepsilon_y = 1, \quad \varepsilon_z = -1$$

Similar structures are disclosed in R A Shelby, D R Smith & S Schultz Science **292**, 77 (2001).

More generally, the permittivities may be a non-unity value so long as one layer has the opposite values to the preceding layer. The meshes 23 are arranged parallel to the plane of the slices 21 and the wires 24 are arranged normal to the plane of the slices 22. The wires could be made of a highly conductive metal such as copper or gold-plated tungsten. A preferred range for the spacing of the grids 23 is 1mm to 50mm, a typical value being 10mm. A preferred range for the spacing of adjacent "bristles" 24 is 1mm to 50mm, typically 10mm. Gold-plated tungsten wires are stiff, and would be self-supporting. The meshes of the layers 23 could be woven, or could be tracks etched on a printed circuit board. The layer thickness would need to be a few unit cells, and thus could be of the order of a centimetre.

Of course, it is not necessary for the layers 22 to have chosen values of permittivities in both the x and y directions. Thus, if the radiation incident on the stack is polarised in, say, the x z plane, the meshes 23 reduce to a planar array of wires (parallel to the x-direction). This would simplify fabrication.

In the case of microstructured magnetic material, Figures 12 and 13 illustrate possible constructions for the case of incoming radiation polarised in the y-z plane.

Thus, Figure 12 illustrates a matrix of split rings as described hereinbefore, which are usually printed on a substrate. The rings 25, 27, seen face-on, comprise columns of rings which form the layers 22 of the stack shown in Figure 9. The real parts of the permeabilities of the layers 22 are given by:

$$\mu_z = 1$$

$$\mu_y = -1$$

where μ_z, μ_y are the magnetic permeabilities in the z and y directions, respectively.

The rings 26, 28, seen end-on, are printed on substrates extending into the plane of the drawing, and form the layers 21 of the stack shown in Figure 9. The real parts of the permeabilities of the layers 21 are given by:

$$\mu_z = -1$$

$$\mu_y = 1$$

where μ_z, μ_y are the magnetic permeabilities in the z and x directions, respectively.

Referring to Figure 13, an alternative way of implementing the embodiment of Figure 9 is microstructured magnetic materials employing Swiss rolls as described herein.

Bundles of short rolls 30, 32 arranged along the axis of the device provide real parts of magnetic permittivity in the z-direction μ_z and the y-direction μ_y as follows:

$$\mu_z = -1$$

$$\mu_y = 1$$

These form the layers 21.

"Log piles" of Swiss rolls 29, 31, 33 arranged with their axes normal to the stack form the layers 22. The real parts of their magnetic permeability in the z-direction μ_z and y-direction μ_y are as follows:

$$\mu_z = 1$$

$$\mu_y = -1$$

For the magnetic material, the device can be made using Swiss Rolls (Pendry et al 2000, Wiltshire et al 2001), with a bundle of short rolls along the device axis to provide $\mu_z = -1$, and a log pile (transverse to the axis)to give μ_x, $\mu_y = -1$.

In both cases, to achieve isotropy in the x,y plane, it would be necessary to include, for the embodiment of Figure 12, extra columns of rings similar to the columns 25, 27, but with their axes extending in the x-directions, one layer for each layer of columns 25. For example, further sets of boards similar to those bearing rings 25, 27 could be arranged between the rings 25, 27, vertically relative to the plane of the drawing and normal to the x-axis, to give $\mu_x = -1$. This would form a square honeycomb structure

similar to the kind disclosed in the Shelby paper. For the embodiment of Figure 13, it would be necessary to include extra log piles of rolls 29, 31, 33, but with their axes extending in the x-direction, again one layer for each layer of the log piles 29, 31, 33. The incident radiation then need not be polarised in the y-z plane. Typical dimensions for the Swiss rolls and their pitch are as for the embodiment of Figure 8.

While the embodiments of Figures 10 to 13 are designed to achieve positive/negative approximately unity values of permeability/permittivity, useful devices may be achieved where the permeability/permittivity is non-unity. Other types of microstructured materials may be used.

Referring to Figures 14 to 16, the third form of imaging device will now be described. This simply consists of a block 34 of closely packed Swiss rolls 35 (as described hereinbefore).

An array of Swiss rolls at resonance comes close to satisfying the condition $\mu_z = \infty$, $\mu_x = 1$ providing that losses are minimised. We work on length scales very much less that the free space wavelength, the magnetostatic approximation. In the case of the Swiss rolls, a characteristic dimension is the diameter, approximately 1cm, compared to the wavelength of $\lambda = 10$m, a factor of 10^3. The system does not transport the image perfectly: the Fourier components degrade with distance. Indeed, the losses dominate the image transfer characteristics. Consider the situation on resonance, when the permeability is approximately $\mu_z = i\beta^2$. Note that precisely on resonance, the permeability has unity real part (which we neglect), and a large imaginary part. The

less lossy the system, the larger that imaginary part, here defined as β^2, will be. If the finest detail in the object (i.e. in our case the spacing of the Swiss rolls) is given by δ, then the corresponding Fourier component,

$$k_{x\max} \approx 1/\delta$$

will propagate a distance,

$$d_{\max} \approx \delta\beta \quad \text{see above}$$

So the smaller the losses (larger β) the further the image can be propagated. Hence if $\beta^2 = 100$ can be achieved then we can tolerate an aspect ratio of 10:1 for the Swiss roll structure i.e. the structure of Figures 14 and 15 can have a length along the axes of the Swiss rolls up to ten times the pitch of the Swiss roll spacing.

One way of looking at the situation is that the magnetic flux is captured by the rolls and each roll represents a pixel. This gives the further flexibility to spread out the rolls to give a magnified image (though not one with more pixels in it).

Referring to Figure 16, which shows the real and imaginary components of the magnetic permeability of the imaging device of Figures 14 and 15 in the direction along the axis of the Swiss rolls, the imaging device is designed to be used at the frequency ω_0. This is the frequency of which the imaginary component of the magnetic permeability peaks.

(Also, the frequency at which the real part of the magnetic permeability passes through unity).

It might be thought that the imaging device would be wholly absorbing of radiation at the resonance frequency, since the imaginary component of the magnetic permeability describes the absorptive behaviour of the magnetically permeable material.

However, reference to the dispersion relation equation (12) shows that the wave vectors are related to the square roots of the permeabilities/permittivities. When it is recalled that the square root of an imaginary quantity has a real component, it can be understood why the imaging device does convey electromagnetic radiation from one end to the other.

The imaging device does not have to be designed to work at the peak of the imaginary component of the magnetic permeability. It can in fact be designed to work at any frequency between the peak of the imaginary component of the magnetic permeability and the peak of the real component of the magnetic permeability. A high magnitude (modulus) of magnetic permeability obtains over this region.

Bundles of Swiss rolls have been used (PCT-A-WO 01/67553, PCT-A-WO 00/41270) to duct electromagnetic radiation, but these are designed to work at frequencies below the peak of the real component of the magnetic permeability, over which region the real component is large but the imaginary component is small. Spatial information is not collected in these prior devices. In particular, in PCT-A-WO 01/67553, spatial

information is coded by magnetic field gradients in the magnetic resonance imaging process.

With the imaging device of Figures 14 and 15, the magnetic flux is captured by the rolls so that each roll represents a pixel. The flux pattern on the incident face is transferred to the emergent face.

The rolls may be made of an 18μm thick conducting film on a 12μm thick Kapton substrate. The rolls may be made by winding 250mm long panels on an 8mm diameter mandrel. This results in rolls of about 9.7 turns and a diameter of approximately 8.5mm. These work at around 35 MHz.

The structure of Figures 14, 15 could be assembled with Rohacell packaging between the rolls to maintain structural integrity.

The third form of imaging device is also applicable to the dielectric case. For example, a resonant electric structure, such as resonant electric dipoles, could be used. The dipoles could be highly tuned antennae or aerials, with their lengths matched to half the wavelength. These would respond to the electric field, and so give a permittivity of the same form as given by the permeability in Figure 16.

Illustrative applications of the invention include its use to provide a virtual antenna. This allows the real generator to be housed and protected from the environment and from interference. The device allows a perfect image of the source to be produced,

from which emission occurs. This would be outside the protective enclosure. All manipulative devices, for example steering machinery etc. could be housed in the protected region, allowing a significant reduction in cost to be achieved, because environmental protection of moving parts would no longer be necessary.

Another application would be to exploit the possibility of shaping the ends of the material (since $\delta\phi = 0$). This would allow a planarised output face or optimised surface shape to be constructed independent of the actual shape of the source.

Moreover, the material could be tapered to expand or concentrate the radiation, as is done in a mode converter.

The operative wavelength of imaging devices according to the invention is the r.f. region, including microwave and mm regions, of the electromagnetic spectrum.

CLAIMS

1. An imaging device comprising a stack of layers spaced apart from each other, each layer having a negative real part of electrical permittivity or magnetic permeability.

2. An imaging device as claimed in Claim 1, in which the electrical permittivity or magnetic permeability is isotropic throughout each layer.

3. An imaging device as claimed in Claim 1 or Claim 2, in which the layers are spaced by a medium having a positive real part of electrical permittivity or magnetic permeability, respectively.

4. An imaging device as claimed in any one of Claims 1 to 3, in which the thickness of each layer lies within the range of from 1/5 to 1/50 of the wavelength of radiation to be imaged by the device.

5. An imaging device as claimed in any one of Claims 1 to 4, in which the number of layers lies within the range of from 2 to 10.

6. An imaging devices as claimed in any one of Claims 1 to 4, in which the number of layers exceeds 10.

7. An imaging device as claimed in any one of Claims 1 to 6, in which each layer comprises an array of elements spaced apart from each other by a distance less than the

wavelength of radiation to be imaged by the device.

8. An imaging device comprising at least two layers, the real part of the component of the electrical permittivity or magnetic permeability of one layer in a direction normal to the layers being negative, and positive in a transverse direction, and the real part of the component of the electrical permittivity or magnetic permeability of the other layer in the direction normal to the layers being positive, and negative in the transverse direction.

9. An imaging device as claimed in Claim 8, including a stack of layers, the layers alternating between those in which the real part of the component of the electrical permittivity or magnetic permeability in a direction normal to the layer is negative and positive in a transverse direction and those in which the real part of the component of the electrical permittivity or magnetic permeability of the layer in the direction normal to the layer is positive and negative in the transverse direction.

10. An imaging device as claimed in Claim 8 or Claim 9, in which the thickness of each layer lies within the range of from 1/5 to 1/50 of the wavelength of radiation to be imaged by the device.

11. An imaging device as claimed in any one of Claims 8 to 10, in which the number of layers lies within the range of from 4 to 20.

12. An imaging device in which the ratio of the magnitude of the component of the magnetic permeability or electrical permittivity of the material of the device in a

direction normal to the incident face to the magnitude of the component of the magnetic permeability or electrical permittivity in a transverse direction, is at least 10.

13. An imaging device is claimed in Claim 12, in which the ratio is at least 30.

14. An imaging device as claimed in Claim 13, in which the ratio is at least 100.

15. An imaging device as claimed in any one of Claims 12 to 14, in which the frequency of radiation to be imaged by the device lies within a range defined by the peak of the imaginary component of the magnetic permeability or electrical permittivity in a direction normal to the incident face and the peak of the real component of the magnetic permeability or electrical permittivity in a direction normal to the incident face.

16. An imaging device as claimed in Claim 15, in which the frequency of radiation to be imaged by the device lies substantially at the peak of the imaginary component of the magnetic permeability or electrical permittivity in a direction normal to the incident face of the device.

17. An imaging device as claimed in any one of Claims 12 to 16, in which magnetic permeability derives from rolls of conducting material arranged normal to the incident face.

18. An imaging device as claimed in Claim 17, in which the length of the rolls is less than ten times the pitch by which the rolls are spaced.

19. An imaging device as claimed in any one of Claims 1 to 18, in which the electrical permittivity or magnetic permeability derives from an array of elements spaced apart from each other by a distance less than the wavelength of radiation to be imaged by the device.

20. An imaging device as claimed in Claim 19, in which the spacing of the elements is less than one half of the wavelength of the radiation to be imaged.

21. An imaging device as claimed in Claim 20, in which the spacing of the elements is less than one fifth of the wavelength of the radiation to be imaged.

22. An imaging device as claimed in Claim 21, in which the spacing of the elements is less than one tenth of the wavelength of the radiation to be imaged

23. An imaging device as claimed in any one of Claims 19 to 22, wherein each element is in the form of a conductive sheet wound as a spiral.

24. An imaging device as claimed in any one of Claims 19 to 22, in which each element comprises a planar ring or spiral.

25. An imaging device as claimed in any one of Claims 19 to 22, in which the layers having the negative real part of electric permittivity comprise an array of conductors extending normal to the direction of the respective layer.

26. An imaging device as claimed in any one of Claims 19 to 22, in which the layers

having the positive permittivity in a direction normal to the layer comprises a mesh extending parallel to the plane of the respective layer.

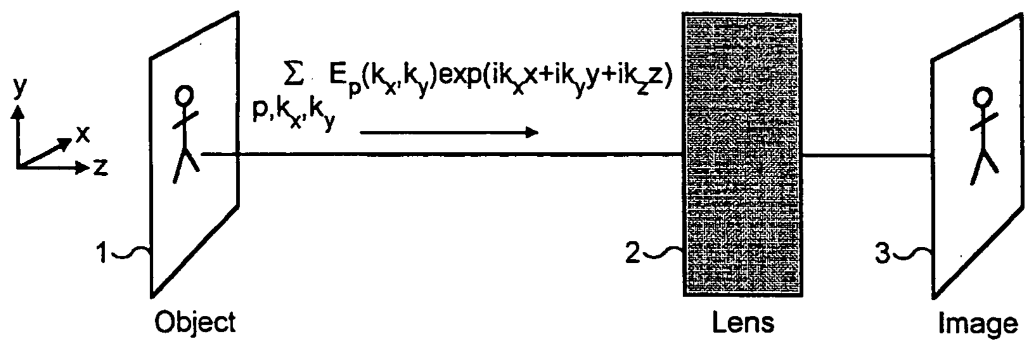

$\sum_{p,k_x,k_y} E_p(k_x,k_y)\exp(ik_x x+ik_y y+ik_z z)$
y
x
z
1
2
3
Object
Lens
Image

FIG. 1

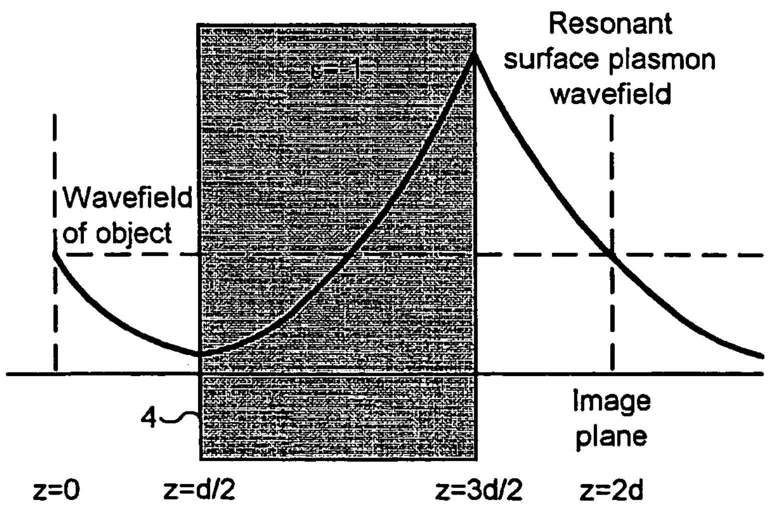

Resonant
surface plasmon
wavefield
Wavefield
of object
Image
plane
4
z=0
z=d/2
z=3d/2
z=2d

FIG. 2

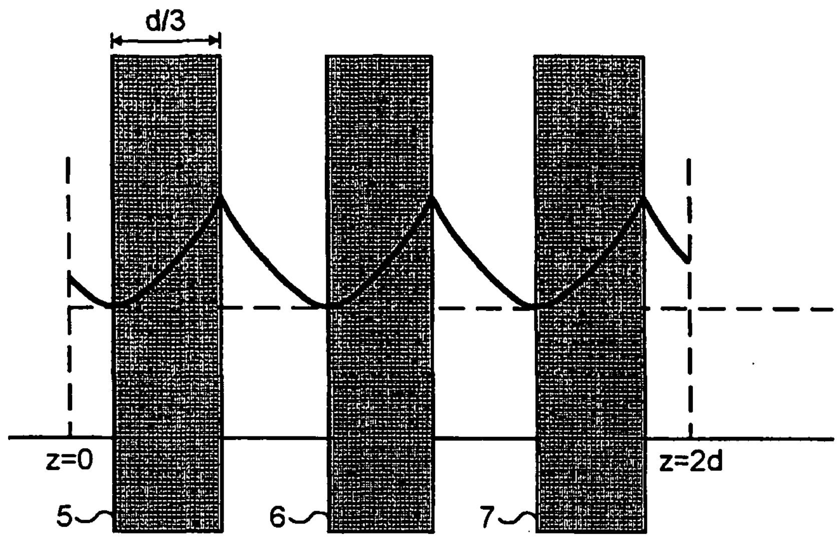


FIG. 3

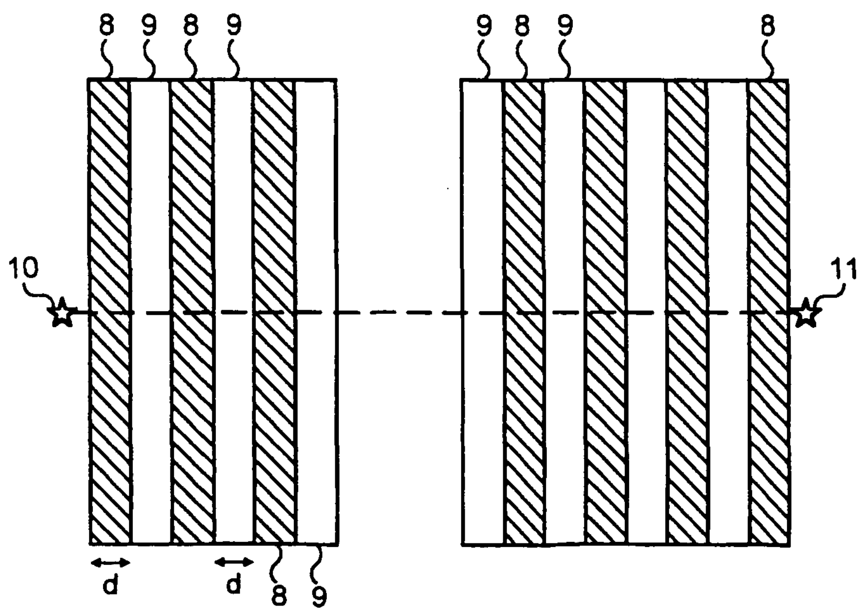


FIG. 4

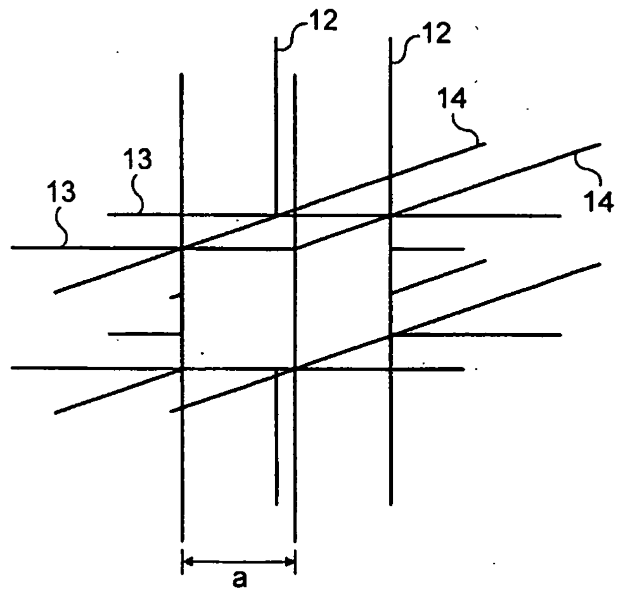


FIG. 5

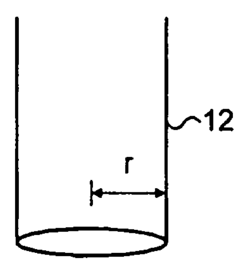


FIG. 6

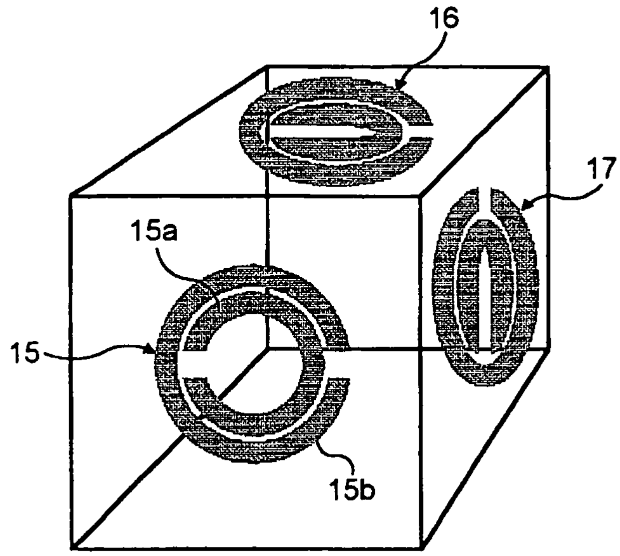


FIG. 7

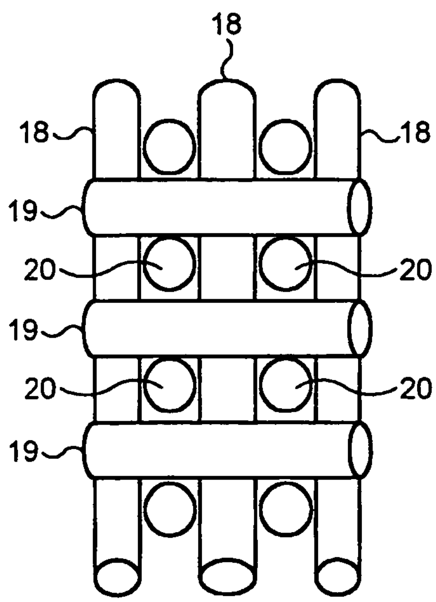


FIG. 8

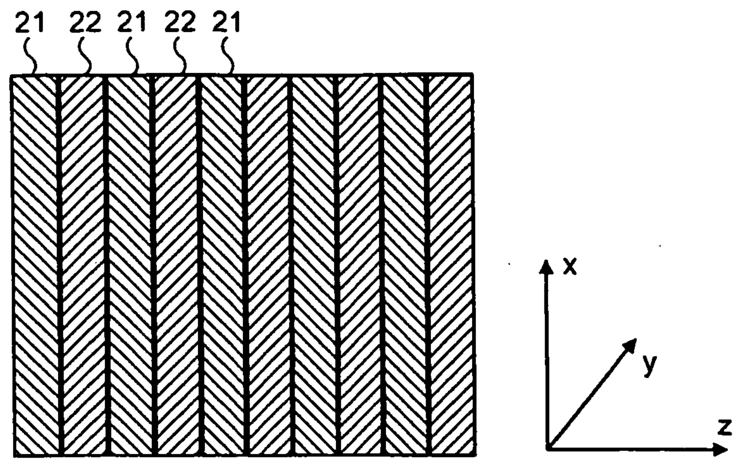


FIG. 9

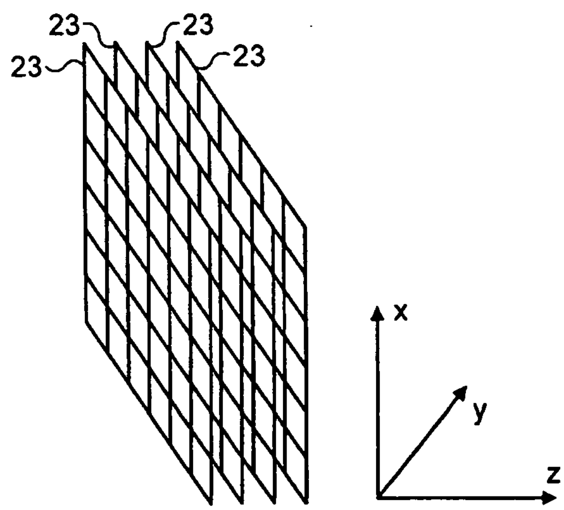


FIG. 10

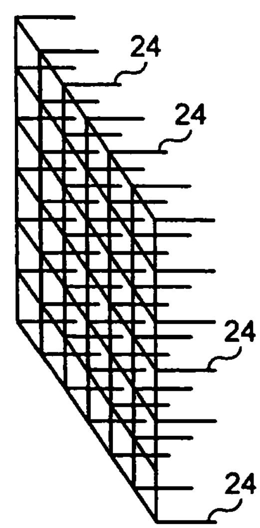


FIG. 11

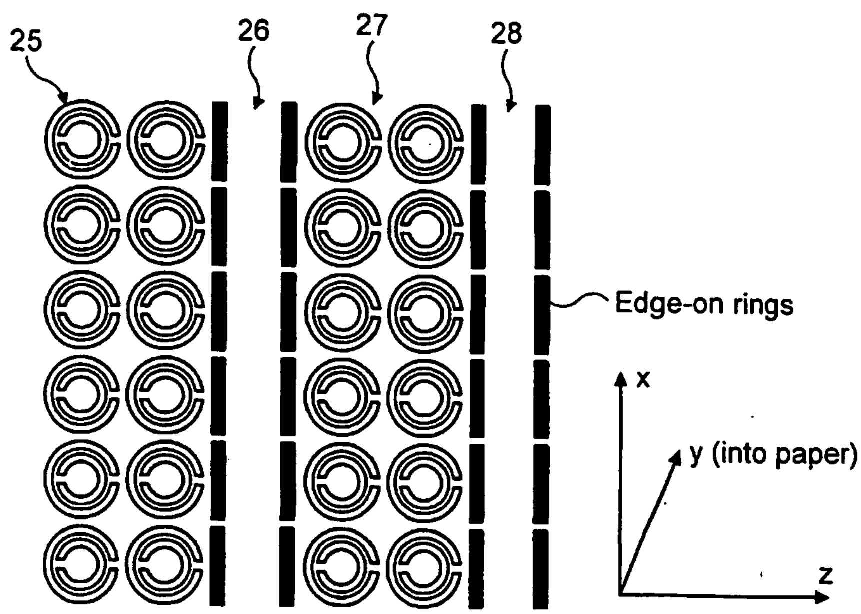


FIG. 12

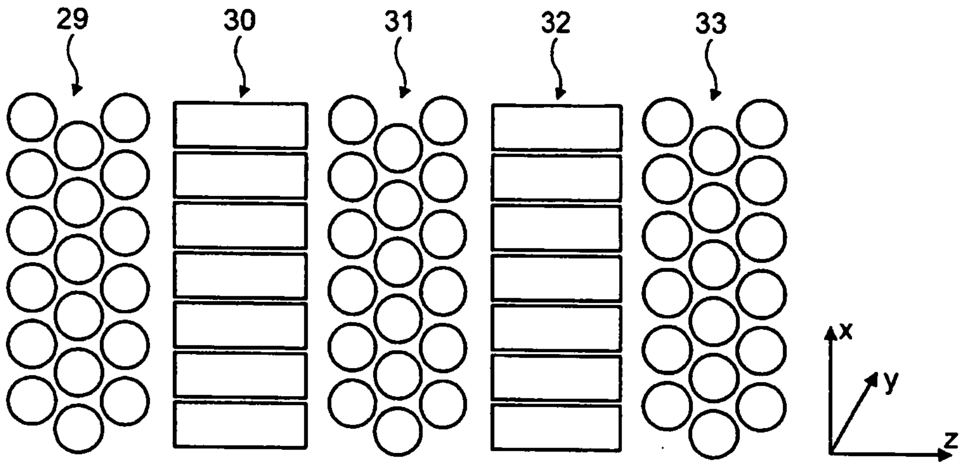


FIG. 13

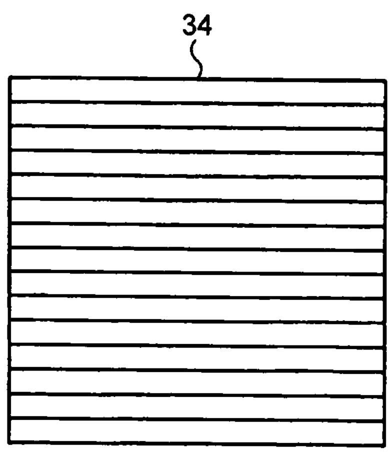


FIG. 14

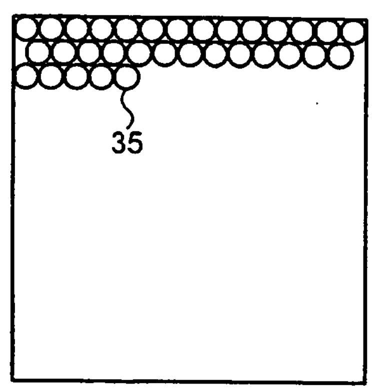


FIG. 15

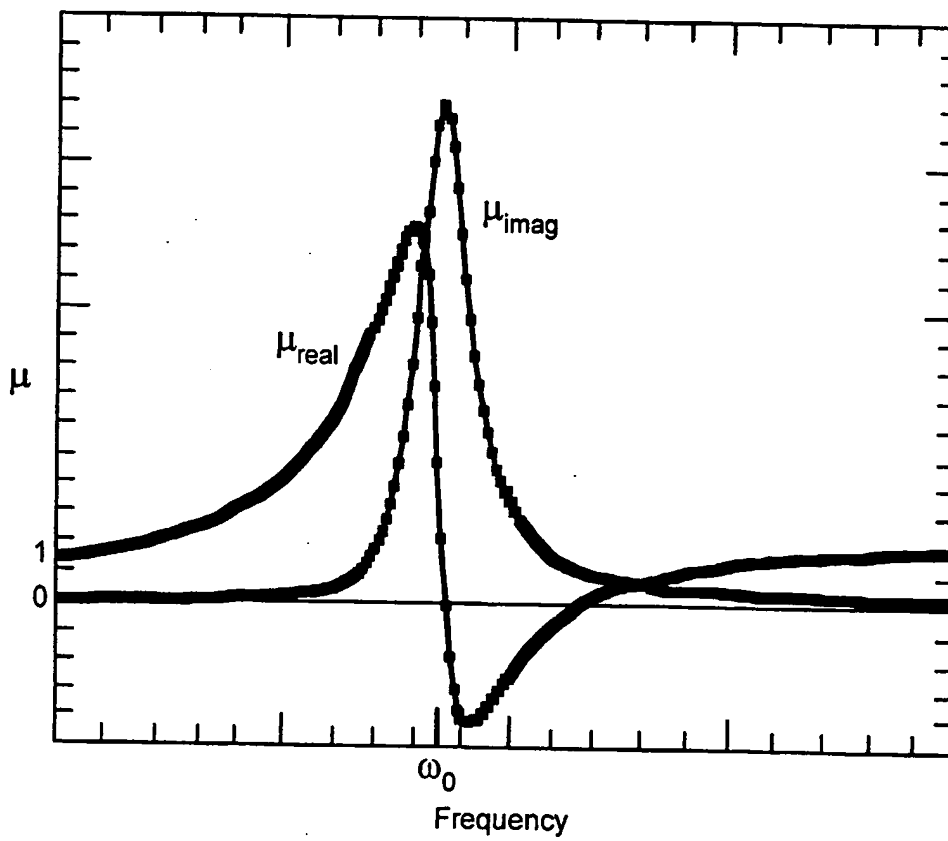


FIG. 16

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 02/03608

A. CLASSIFICATION OF SUBJECT MATTER
IPC 7 H01Q15/10 G02B1/10 G02B5/20 G02B1/00

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 7 H01Q G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

EPO-Internal, INSPEC, WPI Data, PAJ

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	SHAMONINA E ET AL: "Imaging, compression and Poynting vector streamlines for negative permittivity materials" ELECTRONICS LETTERS, IEE STEVENAGE, GB, vol. 37, no. 20, 27 September 2001 (2001-09-27), pages 1243-1244, XP006017293 ISSN: 0013-5194 cited in the application	1-6
Y	the whole document	7,19-26

X	WO 01 71774 A (UNIV CALIFORNIA) 27 September 2001 (2001-09-27)	12-16, 19-22,24
Y	page 17, line 16 -page 18, line 24; figures 1,2A,5A-5B page 24, line 7 -page 25, line 22 page 4, line 10 -page 6, line 18	7,24

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[X] Further documents are listed in the continuation of box C.

[X] Patent family members are listed in annex.

° Special categories of cited documents :

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"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
24 February 2003	11/03/2003

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL - 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Casse, M

C.(Continuation) DOCUMENTS CONSIDERED TO BE RELEVANT

Category *	Citation of document, with indication,where appropriate, of the relevant passages	Relevant to claim No.
X	PENDRY J B ET AL: "MAGNETISM FROM CONDUCTORS AND ENHANCED NONLINEAR PHENOMENA" IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, IEEE INC. NEW YORK, US, vol. 47, no. 11, November 1999 (1999-11), pages 2075-2084, XP000865104 ISSN: 0018-9480 cited in the application	12-25
Y	paragraphs 'III.A!,'III.B!,'III.C!,'OOIV!; figures 7,8,12-14	7,19-23
Y	MOSALLAEI H ET AL: "COMPOSITE MATERIALS WITH NEGATIVE PERMITTIVITY AND PERMEABILITY PROPERTIES: CONCEPT, ANALYSIS, AND CHARACTERIZATION" IEEE ANTENNAS AND PROPAGATION SOCIETY INTERNATIONAL SYMPOSIUM. 2001 DIGEST. APS. BOSTON, MA, JULY 8 - 13, 2001, NEW YORK, NY: IEEE, US, vol. 4 OF 4, 8 July 2001 (2001-07-08), pages 378-381, XP001072138 ISBN: 0-7803-7070-8 page 378-379; figure 2A figures 3-6	19-22, 24,25
Y	WO 00 41269 A (MARCONI CASWELL LTD ;PENDRY JOHN BRIAN (GB); ROBBINS DAVID JAMES () 13 July 2000 (2000-07-13) cited in the application page 3, line 14 -page 4, line 10; figure 1	26
A	TAI G -C ET AL: "Plasma-dielectric sandwich structure used as a tunable bandpass microwave filter" IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, JAN. 1984, USA, vol. MTT-32, no. 1, pages 111-113, XP002232311 ISSN: 0018-9480 paragraph 'OOII!; figure 1	1-6

INTERNATIONAL SEARCH REPORT

Information on patent family members

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PCT/GB 02/03608

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